PASJ: Publ. Astron. Soc. Japan , 1–**??**,

Scaling Relation to Understand Non-Detection of Cold Gas at the Cluster Center

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(Received 2001 July 31; accepted 2001 November 5)

Abstract

Recent XMM-Newton observations of clusters of galaxies have indicated the soft X-ray spectra to be inconsistent with the simple isobaric cooling flow model. There is almost no feature of the cold gas expected from the model. This shows that we have not yet understood the physics of the hot gas in clusters of galaxies well. A quantitative evaluation of the behavior of gas cooling is important not only for understanding the clusters, themselves, but also for studying cosmology and galaxy formation. To clarify the problem of this reported discrepancy, we have studied scaling relations for clusters of galaxies based on the self-similarity assumption. We also propose an observational strategy to solve this problem.

Key words: galaxies:clusters:general — galaxies:clusters:cooling flows — cosmology:large-scale structure of universe

1. Introduction

Previous soft X-ray imaging studies with medium spectral resolution have shown evidence of cooling flows in many clusters of galaxies. In many cases, a simple isobaric cooling flow model (000 [cite]cite.jfet92Johnstone et al. (1992)) was used, and showed a reasonable fit to the observed results. However, recent XMM-Newton observations with high spectral resolution (000 [cite]cite.tam01Tamura et al. (2001); 000 [cite]cite.kaa01Kaastra et al. (2001); 000 [cite]cite.pet01Peterson et al. (2001); 000 [cite]cite.mbfb01Matsushita et al. (2001)) showed that the soft X-ray spectra is inconsistent with the simple isobaric cooling flow model. In A1795, Tamura et al. (2001) showed that the XMM-Newton RGS spectrum obtained from the cluster center can be described by an isothermal model with $kT \sim 4$ keV, and that the upper limit of the emission measure of the cool component ($kT < 1$ keV) is only a few %. Kaastra et al. (2001) showed a significant lack of cool gas below 1.5 keV in the Sérsic 159-03 cluster of galaxies, where a cooling flow of 230 $M_\odot$ yr^{-1} has been indicated from the ROSAT PSPC observation (000 [cite]cite.all97Allen, Fabian (1997)). Peterson et al. (2001) showed that the RGS energy spectrum at the cluster center of A1835 requires a cut-off in the emission measure distribution at 2.7 keV to obtain a good fit with the isobaric cooling flow model. In the Virgo cluster, Matsushita et al. (2001) reported that the emission measure of the cool component below 1 keV is much lower than the expected value from the cooling flow model. In summary, although the central excess of the surface brightness profile has suggested cooling flow and the existence of cold gas, RGS high-resolution spectra at the center of cooling flow clusters did not exhibit the expected emission lines from the cold gas, and the temperature distribution had to be cut-off (cut-off temperature, $T_{\rm cut}$) at 1–3 keV (hereafter, we call this feature the "lack of cold gas" problem). This indicates that we have not yet understood the physics of the hot gas in clusters well.

A proper understanding of the process of gas cooling is important in many respects. First, it is necessary to discuss the cluster gas evolution and its status (for example, whether the hot gas is in hydrostatic equilibrium or not). Second, it is a key to understand the dark matter properties and evolution, since we cannot observe dark matter directly, and its information is obtained only through the observed hot gas properties. Third, clusters are important to study cosmology (for example, to estimate the cosmological parameters), and have been widely used in research. In order to use clusters as a cosmological probe, we need to understand the cluster properties well. Fourth, a study of the cooling gas in clusters gives important information for understanding galaxy formation and evolution, because we can regard galaxies as small mass clusters as a first approximation when we discuss galaxy formation and evolution. Then, cooling is more important in galaxies than in clusters, since the cooling time of the hot gas in galaxy-size halos is shorter than the cosmic time (this feature is different from the clusters' case) and stars are formed from the cooled gas (we have obtained various information about galaxies through stars).

Thus, it is important to understand the cluster hot gas properties. In particular, we need to solve this "lack of cold gas" problem. There are several possibilities to solve this problem: heating, thermal conduction, inhomogeneous metallicity, absorption by cold gas, and non-standard cooling function, and so on (000 [cite]cite.fab01Fabian et al. (2001); 000 [cite]cite.pet01Peterson et al. (2001)). These mechanisms

have both advantages and disadvantages, and it is difficult to judge which is the main mechanism at present.

It seems to be difficult to solve the "lack of cold gas" problem by studying individual clusters, as in previous literature. Thus, in this Letter, we discuss this problem while considering correlations between cluster properties.

2. Scaling Relation

In this section, we consider correlations between cluster properties, particularly between $L_{\rm cool}$ (as defined below) and the gas temperature (or cluster mass). First, we review the self-similarity model briefly and then modify it in order to explain the observed luminosity–temperature relation. We then consider the cooling effect on the cluster properties.

At first, we consider the whole properties of clusters. If shock heating caused by gravitational collapse is the dominant mechanism, it is thus naturally expected that clusters follow a simple scaling model (000 [cite]cite.kai86Kaiser (1986)). We assume that clusters of galaxies are spherically symmetric, and that the hot gas is isothermal and in a steady state with hydrostatic equilibrium. We also assume that the gas number density profile $n(r)$ is described by the conventional β model, $n(r) = n_0/[1+(r/r_{\rm c})^2]^{3\beta/2}$, with $\beta = 2/3$, and that the core radius $r_{\rm c}$ is proportional to the cluster radius $R_{\rm cl}$: $r_{\rm c} \propto R_{\rm cl}$. Assuming that the average mass density in clusters and the gas fraction are identical in all clusters, we obtain the following relations:

$$n_0 \propto M_{\rm cl}^0 \ (=\text{constant}), \quad r_{\rm c} \propto M_{\rm cl}^{1/3}, \quad T_{\rm vir} \propto M_{\rm cl}^{2/3}, \tag{1}$$

where $M_{\rm cl}$ and $T_{\rm vir}$ are the cluster mass and virial temperature, respectively. Hereafter, we assume that the gas temperature, $T_{\rm gas}$, equals the virial temperature ($T_{\rm gas} \equiv T_{\rm vir}$) when gas cooling is neglected. The above relations imply that $r_{\rm c} \propto R_{\rm cl} \propto T_{\rm gas}^{1/2}$. Although whether the observational data satisfies this relation is still in controversy; for example, Vikhlinin et al. (1999) found that the radius of a fixed mean gas overdensity of 1000 is scaled to $T_{\rm gas}^{1/2}$.

If bremsstrahlung emission is the dominant emission mechanism, the bolometric luminosity, $L_{\rm bol}$, is proportional to the gas temperature squared: $L_{\rm bol} \propto {n_0}^2 {r_{\rm c}}^3 T_{\rm gas}^{1/2} \propto T_{\rm gas}^2$. However, the observed luminosity–temperature relation is steeper than this relation; the luminosity is roughly proportional to the gas temperature cubed: $L_{\rm bol} \propto T_{\rm gas}^3$ (e.g., 000 [cite]cite.dsj93David et al. (1993)). There are many arguments to explain this discrepancy. We can divide them into roughly two groups. One is that the gas fraction varies with the cluster mass; the other is that the gas profile deviates from the self-similarity [equation (1)]. For example, the core radius is not proportional to $R_{\rm cl}$, or the cluster radius is not proportional to $T_{\rm gas}^{1/2}$. We briefly discuss the second possibility in section 4. Here, we take the first possibility. We abandon the assumption of the gas fraction being constant, and allow it to vary as a function of the cluster mass, so that the observed luminosity–temperature relation is reproduced (e.g., 000 [cite]cite.dsj93David et al. (1993)). This is expected if non-gravitational processes affect hot gas properties. The pre-heating model is an example (see e.g., 000 [cite]cite.bem01Bialek et al. (2001)), and the variable galaxy formation efficiency is another example (see e.g., 000 [cite]cite.ptce00Pearce et al. (2000); 000 [cite]cite.mtk01Muanwong et al. (2001)). If the galaxy formation efficiency is more efficient in poor clusters than in rich systems, the gas fraction increases with the cluster mass. In order to reproduce the observed luminosity–temperature relation, the gas fraction must be proportional to $T_{\rm gas}^{1/2}$ ($M_{\rm cl}^{1/3}$):

$$n_0 \propto M_{\rm cl}^{1/3}, \quad r_{\rm c} \propto M_{\rm cl}^{1/3}, \quad T_{\rm vir} \propto M_{\rm cl}^{2/3}. \tag{2}$$

We use these relations in the following discussion.

Next, we consider the cooling effect. We assumed the hot gas to be isothermal in the above discussion. However, at the center, the cooling time may be shorter than the cluster age and the cooling mechanism becomes important. We define the cooling radius, $r_{\rm cool}$, as the radius where the cooling time, $\tau_{\rm cool}$, equals the cluster age, $\tau_{\rm age}$: $\tau_{\rm cool}(r_{\rm cool}) = \tau_{\rm age}$. Here, the cooling time is defined as

$$\tau_{\rm cool}(r) = \frac{3n(r)k_B T_{\rm gas}}{\varepsilon(r)}, \tag{3}$$

where $\varepsilon = An^2 T_{\rm gas}^{1/2}$ is the bolometric emissivity and A is a numerical constant. Then, the cooling radius is described as

$$r_{\rm cool} = r_c \left[\frac{An_0}{3k_B T_{\rm gas}^{1/2}} \tau_{\rm age} - 1 \right]^{1/2}. \tag{4}$$

It is to be noted that the value in the bracket does not depend on the cluster mass, since $n_0 \propto T_{\rm gas}^{1/2}$. Then, the gas number density at $r_{\rm cool}$ is given by

$$n(r_{\rm cool}) = \frac{n_0}{[1+(r_{\rm cool}/r_c)^2]} = \frac{3k_B T_{\rm gas}^{1/2}}{2A\tau_{\rm age}}. \tag{5}$$

Hereafter, $T_{\rm gas}$ denotes the gas temperature outside the cooling radius. At $r < r_{\rm cool}$, the gas profile may deviate from the β–model. As a fiducial model, we take the self-similar gas density and temperature profile within the cooling radius,

$$T(r) = T_{\rm gas} f_{\rm T}\left(\frac{r}{r_{\rm cool}}\right), \quad n(r) = n(r_{\rm cool}) f_{\rm n}\left(\frac{r}{r_{\rm cool}}\right), \quad (\text{for} \ \ r < r_{\rm cool}), \tag{6}$$

where $f_{\rm T}$ and $f_{\rm n}$ are functions independent of cluster mass. We then obtain a relation between the luminosity within the cooling radius, $L_{\rm cool}$, and the outer-region gas temperature, $T_{\rm gas}$ (or the cluster mass $M_{\rm cl}$), as

$$L_{\rm cool} = \int_0^{r_{\rm cool}} 4\pi r^2 \varepsilon(r) dr \propto n(r_{\rm cool})^2 r_{\rm cool}^3 T_{\rm gas}^{1/2} \propto T_{\rm gas}^3 \propto M_{\rm cl}^2. \tag{7}$$

That is, the ratio of $L_{\rm cool}$ to $L_{\rm bol}$ is constant. In this case, the cut-off temperature, $T_{\rm cut}$, must be scaled to $T_{\rm gas}$; then,

it is expected that the ratio $T_{\rm cut}/T_{\rm gas}$ is the same in all clusters.

At present, there is no compilation of the correlation between $L_{\rm cool}$ defined above (or $L_{\rm cool}/L_{\rm bol}$) and $T_{\rm gas}$. Therefore, in order to give a rough estimate, we use the data compiled by Allen (2000, table 8) here. It is to be noted that $L_{\rm cool,Allen}$ is estimated from the cooling flow model. $L_{\rm cool,Allen}$ differs from $L_{\rm cool}$, defined above in general, but we expect that there is a positive correlation between $L_{\rm cool,Allen}$ and $L_{\rm cool}$. His results showed that there is no clear trend between $L_{\rm cool,Allen}/L_{\rm bol}$ and $T_{\rm gas}$, although the scatter is large. This may indicate that clusters are roughly described by the scaling relation [equation (6)].

3. Heating Models

The above discussion provides useful information for approaching the "lack of the cold gas" problem. In this section, as an example, we consider the possibility that heating is the main mechanism to solve the problem. The heating model has one possible advantage in that it naturally explains that there is no, or little, mass deposition at the cluster center observationally. Of course, there are problems; for example, the required energy is huge. If we assume a heating source of ΔkT keV in the cluster core with a radius of $r_{100}\times$ 100 kpc and a gas number density of $n_3 \times 10^{-3}$ cm^{-3} in τ_9 Gyr, the required average energy input rate is

$$\frac{U}{\tau} = \frac{3n\Delta kTV}{\tau} = 1.9\times 10^{43}\left(\frac{n_3}{10^{-3}\mathrm{cm}^{-3}}\right)\left(\frac{\Delta kT}{1\mathrm{keV}}\right) \times \left(\frac{r_{100}}{100\mathrm{kpc}}\right)^3\left(\frac{\tau_9}{1\mathrm{Gyr}}\right)^{-1} \quad \mathrm{erg\ s^{-1}}. \tag{8}$$

Since detailed modeling is beyond the scope of this Letter, we do not discuss this problem any more.

Because cooling flow features are seen in many clusters, it is reasonable to assume that they are in a steady state. Within the cooling radius, the cooling time is shorter than the cluster age, by definition. In order that clusters are in a steady state, the cooling has to be balanced with heating. If clusters are self-similar within the cooling radius [equation (6)], then the heating rate has to be proportional to the gas temperature cubed (the cluster mass squared) from the result obtained in the previous section. Hereafter, we assume that the heating rate, Γ, is described by $\Gamma \propto M_{\rm cl}^p$ using a parameter, p.

When the exponent of p equals to 2, clusters can become self-similar within the cooling radius [equation (6)]. In this case, the "lack of cold gas" problem have to be observed in all cooling flow clusters and the ratio $T_{\rm cut}/T_{\rm gas}$ is the same in every cooling flow cluster.

In the case of $p<2$, the heating affects the hot gas more significantly in poor clusters than in rich clusters. Thus, in poor clusters, the ratio of the cut-off temperature to the gas temperature outside the cooling radius becomes larger, that is, the temperature decrement to the center becomes weaker. In rich clusters, the simple isobaric cooling flow model may be a relatively good approximation.

On the contrary, in the case of $p>2$, the heating significantly affects the hot gas in rich clusters. Then, in poor clusters the "lack of cold gas" problem disappears and the simple isobaric cooling flow model is applicable.

At present, several candidates for the heating source are proposed. The above discussion can tell what kind of properties are required in the heating sources. The most popular candidate is supernova. If we consider only normal star formation, the supernova rate is roughly proportional to the total cluster optical luminosity. $L_{\rm cl}$, or the cluster mass: the heating rate due to supernova is proportional to the cluster mass, that is $p=1$. In this case, the "lack of cold gas" problem should be observed only in poor clusters.

Active Galactic Nuclei activity is another candidate. The total optical luminosity of a cD galaxy $L_{\rm cD}$ is proportional to $L_{\rm cl}^{1.25}$ (000 [cite]cite.bah00Bahcall (2000)). If the activity of cD galaxies (e.g., jet kinetic energy) is proportional to the optical luminosity, $L_{\rm cD}$, then the heating rate follows $p\sim 1$. There is another possibility. The cD galaxies are more extended than other giant elliptical galaxies; they show very extended low surface brightness envelopes. The luminosity of the cD galaxy's envelope, $L_{\rm env}$, is proportional to $L_{\rm cl}^{2.2}$ (000 [cite]cite.bah00Bahcall (2000)). If heating is an accompanying result of the formation of the cD galaxy's envelope, then the exponent becomes $p\sim 2$. Then, clusters can become self-similar within the cooling radius [equation (6)].

Next, we consider galaxy–galaxy collisions. If the kinetic energy of galaxies is released in galaxy–galaxy collisions, $\Gamma \sim N_{\rm gal} n_{\rm gal}\sigma_{\rm cl}(m_{\rm gal}\sigma_{\rm cl}^2/2)$, where $N_{\rm gal}$ is the number of galaxies in a cluster and $\sigma_{\rm cl}$ is the velocity dispersion of the galaxies. Since $N_{\rm gal}\propto M_{\rm cl}$ and $\sigma_{\rm cl}\propto M_{\rm cl}^{1/3}$, the heating rate, Γ, is $\sim M_{\rm cl}^2$; that is, $p=2$. In this case, clusters can become self-similar within the cooling radius [equation (6)].

Finally, we consider heating by the magnetohydrodynamic effects proposed by Makishima (see e.g., Makishima et al. 2001). The galaxy motion causes significant magnetohydrodynamic turbulence and frequent magnetic reconnection. Since the kinetic energy of the galaxies is the origin of the heating, the heating rate may be proportional to $N_{\rm gal}\sigma_{\rm cl}^2$. Then, the heating rate, Γ, is $\propto N_{\rm gal}\sigma_{\rm cl}^2/\tau_{\rm heating}$, where $\tau_{\rm heating}$ is the heating time scale. Since we do not know the detail of the heating, we consider the following two simple cases of the heating time scale. One is that the heating time scale is proportional to the crossing time, i.e., $R_{\rm cl}/\sigma_{\rm cl}$. The other case is that the heating time scale is constant. In both cases, the heating rate, Γ, is proportional to $M_{\rm cl}^{5/3}$. Then, the "lack of cold gas" problem may be observed in most clusters; the problem rather tends to become weak in poor clusters.

We only consider cooling flow clusters in the above discussion. However, some candidates of the heating process (e.g., supernovae and galaxy–galaxy collisions) also take

place in the non-cooling flow clusters. They may affect the hot gas properties (such as the temperature structure) in the non-cooling flow clusters as well as in the cooling flow clusters. Observationally, there are small temperature inhomogeneities in the non-cooling flow clusters, except for merging clusters. This indicates that the heating source does not exist in all clusters, but exists only in the cooling-flow clusters. That is, the heating source may be closely related with the cooling properties. If clusters are self-similar within the cooling radius [equation (6)], the heating which accompanies the formation of cD galaxy's envelope is promising, since the existence of cD galaxies is strongly correlated with the existence of cooling flows.

4. Discussion

We considered the case that heating is an explanation of the "lack of cold gas" problem as an example. Of course, there are other possibilities. If inhomogeneous metallicity is the explanation, the cut-off temperature may be determined by the degree of inhomogeneity in the metallicity, which may depend on the history of each cluster. Then, it is expected that the strong $L_{\rm cool}$–$T_{\rm gas}$ relation does not show up and the ratio $T_{\rm cut}/T_{\rm gas}$ changes from cluster to cluster. We consider that observations from XMM-Newton can study these features. Next, we consider a case in which the absorption by cold (neutral) material is the explanation. In this case, the cut-off temperature is determined by the amount of cold gas, which may be proportional to the accretion rate, that is $L_{\rm cool}$. For brighter $L_{\rm cool}$ clusters, the cut-off temperature may become higher. We think this tendency can be checked relatively easily in near-future observations. It is a future work to predict the relation between $L_{\rm cool}$ and $T_{\rm cut}$ for other cases.

In order to reproduce the observed luminosity–temperature relation, we made the gas fraction vary with the cluster mass in the above discussion. There is another possibility that the he gas profile deviates from the self-similar relation [equation (1)]. The self-similar relation [equation (1)] predicts that $r_{\rm c} \propto R_{\rm cl} \propto T_{\rm gas}^{1/2}$, which is supported by Vikhlinin et al. (1999) observationally; but this point is still in controversy. For example, Xu et al. (2001) showed that $r_{\rm c} \propto T_{\rm gas}$ and Mohr and Evrard (1997) insisted that the X-ray isophotal size is proportional to $T_{\rm gas}$. These results indicate that non-gravitational processes are important in cluster evolution (e.g., pre-heating model, 000 [cite]cite.eh91Evrard, Henry (1991); 000 [cite]cite.kai91Kaiser (1991)). Deviations from the self-similar scaling relation [equation (1)] give useful information to understand cluster physics. If we consider these observed relations seriously, our discussion must be changed. Therefore, we performed the same procedure as that in sections 2 and 3, assuming $r_{\rm c} \propto R_{\rm cl} \propto T_{\rm gas}$ instead of $n_0 =$ constant. We obtained roughly the following relations:

$$n_0 \propto M_{\rm cl}^{-1/2} \propto T_{\rm gas}^{-1}, \quad T_{\rm gas} \propto M_{\rm cl}^{1/2}, \quad L_{\rm bol} \propto T_{\rm gas}^{3/2}. \quad (9)$$

Thus, in order to reproduce the observed luminosity–temperature relation we must abandon the assumption that the gas fraction is constant. The gas fraction must be proportional to $T_{\rm gas}^{3/4} \propto M_{\rm cl}^{3/8}$, then, $n_0 \propto T_{\rm gas}^{-1/4}$. We thus obtain $L_{\rm cool} \propto T_{\rm gas}^{27/8}$, or steeper, depending on the first term in the brackets of equation (4) being much greater than 1 or not, instead of $L_{\rm cool} \propto T_{\rm gas}^3$ in section 3. If clusters are self-similar within the cooling radius [equation (6)], the heating rate, Γ, has to be proportional to $M_{\rm cl}^{27/16}$, or steeper, instead of $M_{\rm cl}^2$ in section 3. This difference may not significantly affect the rough discussion about the heating source in this Letter.

On the other hand, recently, Ota (2001) suggested that clusters have two different length scales of about 50 kpc and 200 kpc for each core radius, assuming the Hubble constant to be 50 km s^{-1}Mpc^{-1}. Although we have not understood the origin of these two length scales, here, we tentatively consider that the larger core size describes the cluster properties. Since the core size does not correlate with the temperature strongly, we assume $r_{\rm c}$ to be constant as another example (it is hard to consider cluster size is constant, thus we do not assume $r_{\rm c} \propto R_{\rm cl}$) instead of $n_0 =$ constant. Then, we obtain roughly

$$n_0 \propto M_{\rm cl}^{2/3} \propto T_{\rm gas}, \quad R_{\rm cl} \propto M_{\rm cl}^{1/3}, \quad T_{\rm gas} \propto M_{\rm cl}^{2/3}. \quad (10)$$

In this case, we obtain $L_{\rm bol} \propto T_{\rm gas}^{5/2}$, thus the gas fraction must be proportional to $T_{\rm gas}^{1/4} \propto M_{\rm cl}^{1/6}$ in order to reproduce the observed luminosity–temperature relation. Then, $n_0 \propto T_{\rm gas}^{5/4}$ and we obtain $L_{\rm cool} \propto T_{\rm gas}^{21/8}$ or steeper depending on the first term in the brackets of equation (4) being much greater than 1 or not. If clusters are self-similar within the cooling radius [equation (6)], the heating rate has to be proportional to $M_{\rm cl}^{7/4}$, or steeper. This difference may not significantly affect the rough discussion about the heating source, too.

Recently, Chandra observations have shown that some clusters have a complex X-ray surface brightness distribution, arising from the presence of radio lobes (e.g., the Perseus cluster: 000 [cite]cite.fse00Fabian et al. (2000); the Hydra A cluster: 000 [cite]cite.mwn00McNamara et al. (2000); A2052: 000 [cite]cite.bsm01Blanton et al. (2001)). The size of the radio lobes is about several-times 10 kpc, which corresponds to the size of the region where the "lack of cold gas" problem occurs. At present, there is no evidence for shock-heated gas surrounding the radio lobes. Therefore, the radio activity is not likely to be a major source of energy input. However, it is possible to affect our discussion through modifying the gas distribution. We think that the connection between the effect of radio lobes on the surrounding gas and the "lack of cold gas" problem must be thought about in future work.

At present, the "lack of cold gas" problem has been reported in only four clusters: A1795 ($T_{\rm vir} \sim 6$ keV, 000 [cite]cite.tam01Tamura et al. (2001)), Sérsic 159-03 ($T_{\rm vir} \sim 3$ keV, 000 [cite]cite.kaa01Kaastra et al. (2001)), A1835 ($T_{\rm vir} \sim 8$ keV, 000 [cite]cite.pet01Peterson et al. (2001)) and the Virgo cluster ($T_{\rm vir} \sim 2.5$ keV, 000 [cite]cite.mbfb01Matsushita et al. (2001)). The contra-

dictory cases, i.e., cooling flow clusters without the cut-off temperature, are not yet reported by XMM-Newton. Thus, at present it may be premature to discuss the self-similarity; for example, studying the relation between $T_{\rm cut}$ and $T_{\rm gas}$. However, it is worth pointing out that this problem has been reported in a relatively low temperature cluster; Sérsic 159-03, and the Virgo cluster. Thus, this feature must be universal and this point needs to be taken into account in considering the problem. If heating is the explanation, it is likely that the exponent of the heating, p, is around 2.

We would like to thank an anonymous referee for his/her useful comments. We would also like to thank Prof. T. Ohashi for useful comments. This research was supported by a Grant-in-Aid for Scientific Research from the Ministry of Education, Science, Sports and Culture (No. 12304009).

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